REMARKS

The specification is being amended to remove any reference to Fig. 2 since Fig. 2 was inadvertently omitted from the filed application.

The application, as amended, should now be in condition for prosecution.

Respectfully submitted,
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FIGURE[s 2 and] 2A [are] is a cross section[s] of a WEC[s] which may be used to practice the invention;

FIGURE 3 is a simplified schematic diagram of a three-phase generator, driven by a motor contained within a WEC, for the application thereto of an optimum load in accordance with the invention;

FIGURE 4 is a waveform diagram illustrating the heavy modulation of the generator output voltage;

FIGURE 5 is a simplified block diagram of part of a system embodying the invention;

FIGURE 5A is another block diagram of a system embodying the invention;

FIGURE 6 is a schematic diagram of a rectifier circuit which may be used in systems embodying the invention;

FIGURE 7 is a highly simplified diagram of an inductive element used to resonate with a mechanical to electrical converter exhibiting capacitive characteristics;

FIGURE 8 is an electrical equivalent circuit of a system embodying the invention;

FIGURE 9 is a simplified block diagram of a system embodying the invention;

FIGURE 9A is another block diagram of a system embodying the invention;

FIGURE 9B is a diagram of an inductor network suitable for use in practicing the invention;

FIGURE 10 is a block diagram illustrating that a wave energy converter (WEC) for use in practicing the invention may be either inductive (LEFF) or capacitive (CEFF);

FIGURE 11 is a plot of normalized effective wave height versus frequency;

FIGURE 12 is a plot of normalized buoy efficiency as a function of buoy length;

FIGURE 13 is a plot of normalized values of Power Out for different values of buoy lengths;

FIGURE 14 is a plot of optimal length of a buoy as a function of different water depths; and

FIGURE 15 is a plot of the optimal length of the buoy as a function of wavelength, λ.

DETAILED DESCRIPTION OF THE INVENTION

To better explain the invention, reference will first be made to the simplified diagrams of various WEC structures shown in Figs. 1[, 2] and 2A.

Figure 1 is a sketch for identifying various relevant dimensional parameters of a system which may be used to practice the invention deployed in a body of water. Figure[s 2 and] 2A [are] is a cross-section[s] of a WEC[s] identifying certain of their key elements which are used to practice the invention.

This invention teaches and shows: (a) that various portions of a mechanical, hydraulic, electromechanical and electrical subsystems may be represented by a single electrical equivalent circuit which may be used for further development of the system; (b) the development of a mathematical model to characterize a buoy system, and more particularly, a WEC; (c) a method of extracting electrical power from the WEC; (d) apparatus and methods to optimize power transfer from the WEC to a load; and (e) that the length (L) of the buoy (i.e., the tubular structure) may have an optimum range of values.

Thus, the invention resides, in part, in recognizing and determining which factors are important in ascertaining the length of a buoy and how to determine an optimal value of buoy length as a function of water depth (Dw) and the length of the waves operating on the buoy. The invention also resides, in part, in identifying the relationship between a buoy power generation system and the electrical loading on the system. For ease of illustration, in the discussion to follow, reference and assumptions are made which apply specifically to a cylindrically (tubular with piston) shaped WEC of the type shown in Figs. 1[, 2] and 2A. However, it should be understood that the invention is applicable to other structures used to convert naturally occurring and recurring forces into electrical energy.

1.0 System Differential Equation

Referring to Figs. 1[, 2] and 2A, the basic WEC buoy differential equation is, by balance of forces, given by

$$\mathbf{F_{IN} \sin\omega t = M_{WC}\, \partial V_P/\partial t + F_C} \qquad \textbf{(1)}$$

corresponding equations for piston stroke S_P, power out Pout, and optimum resistive load $(R_L)_{OPT}$ are presented below.

1.1 Stroke:

$$S_P = V_P/j\,\omega = V_{PM}/(j\omega(1+j\omega\tau)) \text{ meters} \quad (5)$$

Note: only the real part of equation (5) need be considered.

Optimizing Power Extraction

A significant aspect of this invention is to relate electrical power extraction to the buoy system differential equation and to determine the optimum extraction strategy. Fig. 3 shows the equivalent circuit of an electric generator 42 used in Fig[s]. [2 and] 2A. The electric generator is a 3ϕ generator located within the buoy. (Voltages shown are RMS values.) In Fig. 3, the only voltages externally available are nodes labeled "A", "B", and "C" as the neutral "N" is not brought out. Because of this, power is extracted by Δ connected loads (R_L in the figure) across the 3 line-to-line voltages ($v_{L\text{-}L}=\sqrt{3}\, v_{L\text{-}N}$).

1.2 Electrical Output Power (per leg or 1/3 P_T):

$$P_{OUT} = v_{LL}^2/(2R_L) = K_G^2\, \omega_S^2/(2R_L) = K_G^2\, |V_P|^2/(2\, r_0^2\, R_L)$$

$$= F_{IN}^2\, R_L\, r_0^2/\, (2\, K_T^2\, (1+ \omega^2\, R_L^2\, C_{EFF}^2)) \quad (6)$$

1.3 Optimum Load Resistance:

The optimum load resistance is that value of R_L which maximizes the generator power output P_{OUT}. By inspection of Eq. (6), it is seen that P_{OUT} goes to zero at $R_L = 0$ and ∞ and is positive in between so that an optimum does exist.

Alternatively, the controller 54 may be pre-programmed and loaded with statistical data as to ocean wave and climate conditions so as to control the system response with a view to optimizing the power transfer. The signals S1 (or S1A) and S2 and the controller action on inverter 50 thus effectively control the value of R_L seen by the generator 42 so that the system is operated such that the effective load is made or kept equal to R_{LOPT}. It is significant that, in systems embodying the invention, the available or average input power, as well as the desired optimum load, are factored into the equation to optimize power transfer.

It should be emphasized that a particular rotary hydraulic motor-rotary electrical generator was used for purpose of example and that any other suitable motor generator combination may be used (e.g., a rack and pinion combined with a generator, or a linear electromagnetic generator instead of a hydraulic rotary generator) may be used. Likewise, many different types of converters responsive to naturally recurring sources of energy (for example, a water flow turbine) may be used instead of the WECs shown herein. The cylindrical tube shown in Figs. 1[, 2] and 2A are only for purpose of illustration. The invention may be used in any system including any shell (e.g., container, cylinder, cone) of arbitrary shape suitable for containing a volume of water which in combination with a piston like structure can capture the force of the waves and convert that force to a mechanical motion or force which is then converted to electrical energy.

A slightly more detailed and modified version of Fig. 5 is shown in Fig. 5A. Fig. 5A illustrates that the any of the following signals may be applied as inputs to

42 sees RL(OPT). Concurrently, the controller 54 can switch into the circuit the optimum inductance required to achieve resonance as a function of an input (S1) from the wave sensor 56a, or form the CEFF monitor 57 or form any other input to the controller 54. The controller may use a look up function or an algorithm with the frequency of the waves and/or CEFF as independent variables.

Alternatively, the controller 54 can vary the inductance slowly over several wave periods (cycles) during which the system "hunts" for maximum power transfer points. This may be accomplished by periodic computation of power per wave which in turn can make use of a number of different sets of parameters (e.g., Power is equal to voltage times current, or speed times torque, or velocity times force).

Alternatively, the controller may also be used to send signals to an AC to DC converter such that the voltage leads or lags the current and at the same time control the impedance to be approximately equal to RL(OPT). Thus, the effective inductance to resonate with the electromechanical system may be accomplished in a different manner.

In figures 1[, 2] and 2A the equivalent impedance is characterized as being capacitive and equal to C_{EFF}. To achieve resonance an inductive element is inserted into the circuit. However, it should be appreciated that the equivalent impedance of a WEC functioning differently than the WECs of Figs. 1[, 2] and 2A may be characterized as being inductive and equal to L_{EFF}. For such a WEC, a capacitive component would be inserted in the generator output loop having a value to resonate with L_{EFF}. This is shown in a general manner in Fig. 10, where

a resonating network 510 is placed in the power transfer loop. If the output impedance of the mechanical force to electrical energy converter 42a is characterized as ωL_{EFF} then, the resonating network is controlled and made capacitive such ωL_{EFF} is equal to $1/(\omega C_{EFF})$.

Regarding the piston shown in Figs. 1[, 2] and 2A, note that the piston may be any inner body component such that its movement within a shell (tube) causes a mechanical, electrical or electromechanical response to be generated.

DETAILED DESCRIPTION OF THE INVENTION RELATING TO THE LENGTH OF THE BUOY

As discussed above, a WEC was analyzed and it was shown and taught that there is an optimum value of generator load resistance which maximizes power transfer. The value of the optimum load resistance depends on the geometry of the WEC (buoy) and certain features of the hydraulic system and the type of electric generator. In one embodiment, the electric generator may be a permanent magnet type electric generator which avoids the need to apply power to magnetize. However, it should be understood that any suitable electric generator may be used.

In the discussion above, the focus was on the generator load and its interaction with the effective capacitance of the water mass in the buoy. The concepts and corresponding structures, discussed above, were tested in a wave tank which proved their workability.

The improvement now being considered is the recognition that the length "L" of the buoy (WEC) of the type shown, for example, in Figs. 1[, 2] and 2A, also